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CAVITATION RESEARCH

A PROGRESS REPORT

SAFE HARBOR WATER POWER CORPORATION

Subsequent to this report, presented in Boston, March 3, 1933, a number of interesting developments have been made in several phases of the general program of research. These studies point definitely to an advance in our knowledge of the characteristics of cavitation and of precautions to be observed in testing. As soon as the results can be sufficiently confirmed and correlated to justify a statement of conclusions, they will be made the subject of a subsequent report.

Baltimore, Md., March 24, 1933

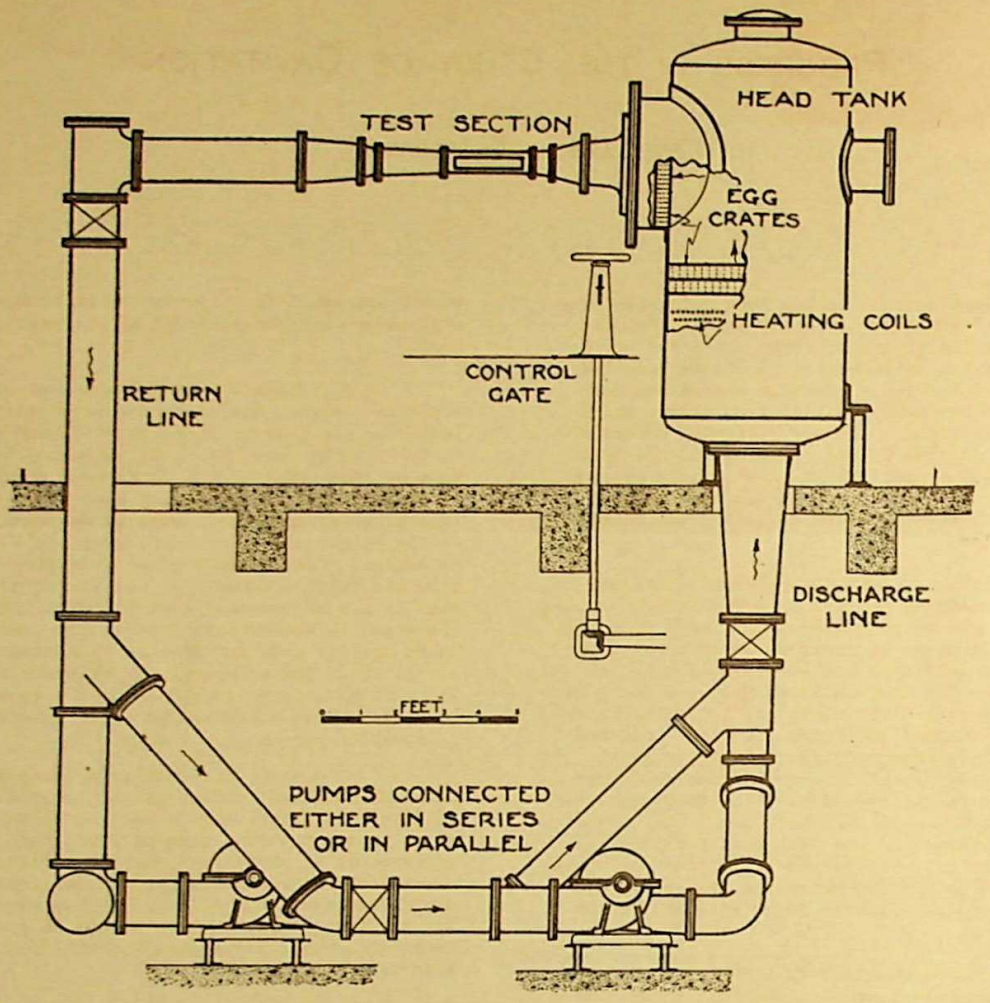

Fig. 1, General Arrangement of Apparatus Used by Prof. Spannhake

This paper was presented at a meeting of the Hydraulic Power Committee of the New England Electric Utilities Engineers, Hotel Statler, Boston, Mass., March 3rd, 1933. The members of the committee had visited during the morning session the River Hydraulic Laboratory directed by Prof. Kenneth Reynolds, and the cavitation research laboratory of Prof. Wilhelm Spannhake at the Massachusetts Institute of Technology. Here they were shown the work which is sponsored by the Safe Harbor Water Power Corporation, and it was the purpose of this paper to outline the general program of cavitation study of which this is a part.

Prof. Spannhake's test stand was in operation illuminated by Prof. Edgerton's stroboscope so that by visual inspection the formation and collapse of cavitation could be studied for different stages of development. Moving pictures taken at the rate of five-hundred exposures per second, by which means the action could be slowed down thirty times, were shown by Prof. Edgerton. There were numerous examples of materials which had been pitted by cavitation produced artificially, as well as diagrams showing the pressure distribution in the test section. Mr. E. W. Spannhake demonstrated the mechanical analyzer by which the amount of air dissolved in the water could be determined. The members of the committee had the opportunity of examining the apparatus in detail and discussing the research with members of Prof. Spannhake's staff which included in addition to Prof. Spannhake's son, Dr. H. Peters who carried on the work in Prof. Spannhake's temporary absence, Dr. C. P. Kittredge, Mr. J. K. Vennard and Mr. H. N. Halberg.

PROGRESS IN THE STUDY OF CAVITATION

BY CARROLL F. MERRIAM[1]

Although cavitation has been recognized for many years as a difficulty encountered with Francis turbines, in America it has not been given the serious consideration which is warranted by the introduction of the propeller turbine. Certain wheels had been known to deteriorate very rapidly from causes which were little understood. It was generally conceded that by slight changes in the curvature of the buckets, these troubles could be at least partly overcome. Still effort to solve the problem was haphazard with very little real investigation regarding the fundamental principles.

It had been realized that draft head was one of the controlling factors, and statistical studies have been made which showed that wheels with high settings had a greater tendency to be affected than wheels with low settings. A concrete example is seen in the double runner units at Holtwood where in twenty-three years no difficulty has been experienced with the lower runners, while on the other hand the upper runners have required extensive repairs and much attention to prevent irreparable damage. The difference between the two is that the draft head for one is much greater than for the other. In attempting to take advantage of the fact that turbines can theoretically be set at a considerable distance above tailwater, that is, at any elevation not exceeding the barometric height, it was found that cavitation increased.

The other important factor which was found to have a profound influence is specific speed. Here again in an attempt to take advantage of the attractive possibilities offered by higher specific speeds, difficulties were encountered. In evaluating these factors, Prof. Moody contributed to our knowledge of hydraulic design by the development of a cavitation coefficient which expressed the extent to which a design may be considered conservative or safe.

The results from the use of his coefficient are not entirely consistent, as evidenced by the fact that in some cases runners have been found to pit even though operated at all times conservatively from this point of view, and indicate that the phenomenon is exceedingly complex, and is one concerning which we have little definite knowledge.

As a result of Dr. Thoma's visit to the United States, it became more generally understood in this country that cavitation was associated with a reduction of pressure to the vapor pressure of water so that it actually boils and forms voids filled with water vapor. The work which he had done in Munich, and concerning which he lectured, dealt principally with determining experimentally under what conditions runners of a given design would exhibit this phenomenon. Since the computation of pressure distribution throughout a turbine is exceedingly complex and at best uncertain, it was natural therefore that Dr. Thoma's approach to the problem should be essentially experimental. His method was to test a runner under constant head, in the meantime varying the headwater and tailwater levels so that the absolute pressure at all points in the turbine could be caused to vary through a wide range. He assumed that cavitation would take place as soon as the pressure at some point was reduced to that of the vapor pressure of the water, and would be evidenced by an abrupt change in efficiency which he observed on increasing the draft head.

Dr. Thoma's commonly accepted cavitation coefficient, sigma, can perhaps best be visualized by imagining the turbine gates to be closed when the cavitation had just begun, which means that the pressure at some point on the runner was equal to the vapor pressure. The pressure that would exist at this point after gate closure is obviously the barometric height minus the draft head, or distance above tailwater. The pressure would thus have been raised from the vapor pressure to this static pressure. From this it may be reasoned that the conditions under which the wheel is tested have lowered the pressure at this point by this same amount. As this reduction is proportional to the square of the velocity of the water which in turn is proportional to the square root of the head, it may be expressed as a percentage of the total head, which percentage is sigma.

The early European experience with propeller runners added greatly to the realization that studies of cavitation were necessary, for disappointments showed that the laws of similitude, by which the performance of prototypes could be predicted from models, failed unexpectedly, and for reasons which must have seemed mysterious. In the case of propeller turbines, the situation became so grave that European investigators gave a great deal of serious attention to this subject.

At the time of Dr. Thoma's visit there was no laboratory on this continent equipped especially for carrying out such research, and it was appreciated that if American manufacturers were to build successfully, and if operating companies were to operate successfully, large propeller runners, it would be necessary to have some means of testing runner designs to determine their suitability with respect to cavitation. Some agitation was started on the part of far-seeing individuals who attempted to arouse sufficient interest in the founding of such a laboratory, but unfortunately these plans failed to mature.

About this time it was found that the laboratory of the Shawinigan Water and Power Company at Shawinigan Falls could, with certain limitations, be used very satisfactorily for tests of this kind. Although it was not possible to vary the headwater elevation as Dr. Thoma had done, nevertheless the tailwater elevation could be adjusted very conveniently. However, since raising the tailwater reduces the total head, then simply by regulating the speed of the runner to maintain constant phi, or ratio between the speed of the tip of the runner blade and the spouting velocity corresponding to the head, the effect would be the same as though the head had been held constant and headwater raised.

By taking advantage of this possibility, the Shawinigan laboratory has done a large amount of the pioneer work in America.

Careful consideration was given on the part of the Pennsylvania Water & Power Company to possible

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[1]Pennsylvania Water & Power Company, Baltimore, Md.

use of the Shawinigan facilities, but on account of the impossibility of securing the use of them except for a limited time, it was decided to construct a cavitation laboratory at Holtwood. In general, this follows the scheme of Dr. Thoma, but differs principally in the method of varying the water levels. Dr. Thoma used telescoping overflows for adjusting both head and tailwater. At Holtwood a large head tank was constructed which could be filled or emptied as desired. The tailwater, on the other hand, discharged into a tank which could be subjected to pressure or vacuum to correspond to the changes in draft head, the water being allowed then to flow by gravity from this chamber into the river through a control gate.

Another notable laboratory devoted to work of this kind was constructed at about the same time by the Allis-Chalmers Manufacturing Company of Milwaukee.

The cavitation experiments at Holtwood were carried on in much the same manner as at Dr. Thoma's laboratory. The characteristics of the various models were investigated, first by determining the horsepower, discharge and efficiency against phi for various combinations of gate and blade angle, the purpose being to determine the envelope of the efficiency curves for each blade angle. Following this series, tests were subsequently made for each combination of phi, blade angle and the three gates which fell most nearly on the envelope relation determined as above. In each case the headwater and tailwater levels were varied, but at the same time constant phi was maintained thus giving a range of values of sigma. The efficiency and discharge were determined and plotted against sigma. The point of cavitation, or rather the value of sigma at which cavitation began, could be determined either by the drop in efficiency or by the increase in discharge. By finding this point for each combination of blade, gate and phi, the cavitation characteristics of the model could be plotted and the proper setting of the unit determined.

The work so far had been carried on with little regard to the fundamental theories of cavitation, as it made little difference whether the effect was mechanical or chemical. The aim was to secure a design which would be the most economical from the point of view of output, efficiency, and cost of the setting.

Since the Safe Harbor plant went into service, the units have been most carefully watched, and frequent inspections are made to determine what effect cavitation may have upon the blades. The loading is scientifically controlled, based on the results obtained in the laboratory, so that at no time, except in case of emergency, and then only for short periods, would the units be called upon to operate under conditions leading to disastrous results. Some studies were made by means of a vibration recorder which indicated that at about the limit expected from laboratory experience there was increase in the vibration of the man-door in the draft tube. It was also found that wider opening of the blades was conducive to quieter operation, a result which agreed with the fact that laboratory tests had shown that wider blade angles were less subject to cavitation.

Inasmuch as the Safe Harbor units are the first large Kaplan turbines to have been built in America, it was most desirable to see how the cavitation characteristics determined in the laboratory would compare with the field. Provisions have been made for tests by the index method. At present a sufficiently wide range of operating conditions have not been secured to obtain conclusive results, but the Test Department is ready to take advantage of those times when the head is below normal by reason of first, low forebay and normal tailrace, and second, normal forebay and high tailrace. A somewhat limited range of variation of sigma may thus be secured and comparison can eventually be made with the laboratory. We have just recently been able to make tests under the first of these conditions, but so far no flood large enough to give the necessary complementary conditions has occurred.

Pitting was first found near the leading edges of the blades, but further progress has been practically stopped by alteration of the profile of these edges to give a more favorable pressure distribution. Pitting in other localities appears to be associated with low spots in the casting, and it is believed that with machined blades, pitting from this cause would not be likely to occur.

In addition to the laboratory studies, supplemented by field observations and inspections, it was felt that we should have a better knowledge of the phenomenon of cavitation itself and its relation to the pitting caused by it. Opportunity for investigating this phase was favored by securing the services of Prof. Wilhelm Spannhake who in the fall of 1931 succeeded Dr. Thoma as Visiting Professor of Hydraulics in the Massachusetts Institute of Technology.

Prof. Spannhake had already conducted elaborate experiments in cavitation in a laboratory somewhat different from that of Dr. Thoma, inasmuch as the water is always confined to a closed system, the turbine being located in the connection between two tanks, the pressure in both of which could be varied as desired. Such an arrangement had the advantage that the tests could be conducted at widely varying heads, inasmuch as the whole was removed entirely from the effect of the atmospheric pressure, which is that term entering into the equation for sigma that cannot be altered in proportion to the scale of the model.

Shortly after Prof. Spannhake came to America, he presented in a paper before the Hydraulic Power Committee of the Engineering National Section, N.E.L.A., February 1932, see Publication No. 222, an interesting theory concerning the nature of cavitation. In brief, the action is essentially mechanical rather than chemical. Bubbles of vapor are formed as soon as the pressure at any point of a turbulent, or impure, liquid is reduced to its vapor pressure. With recovery of pressure, the bubble is collapsed, the vapor condensing. However, if air is present in even a very small quantity, this air comes out of the solution prior to the formation of vapor. Then when the bubble is formed it will contain not only vapor but a mixture of air. Although readily drawn out of solution by reduction in pressure, the air finds difficulty in returning to the liquid at the moment of collapse of the bubble and, consequently, remains to receive the concentrated energy of the inrushing walls of water. It is not definitely known what form this concentrated energy may take, but it is believed that although the bubble is surrounded by a cooler medium, and although it must have a very small ratio of volume to surface, nevertheless for an exceedingly small period of time it may be compressed to an enormous pressure, and at the same time be heated to a high temperature. Now if the small parcel of concentrated energy happens to come in contact with a solid surface in which there are minute fissures, the bubble of air may become lodged and then either explode with tremendous violence, or else transmit sufficient heat to its surroundings to raise the temperature to the melting point, or in any case it may easily cause the particles in the surface to become dislodged so that the material itself disintegrates.

Together with Prof. Foettinger, Prof. Spannhake had, in 1916, done some notable work at Hamburg, which was reported in the 1926 Hydraulische Probleme. In this connection he studied the formation of cavitation on a vane inserted in a box, one side of which was formed by plate glass and through which a current of water flowed. Among other results, he obtained an effect which was then considered remarkable, a distinct pitting on the plate glass itself. This is one of the most striking examples which showed that the pitting is not necessarily of chemical nature. It has since been demonstrated that not only is glass subject to the effect of pitting, but also it is one of the most vulnerable of materials. It is believed that the

particular quality which contributes to weakness of glass in this respect is its extreme brittleness.

In order to study cavitation under controlled conditions, Prof. Spannhake proposed a plan for producing it in a rectangular passage shaped in one plane like a Venturi tube, and faced with glass plates that served for windows. In order to furnish the flow of water, centrifugal pumps were arranged so that they could be connected either in series or in parallel, depending upon whether high head or large quantity was desired. These pumps discharge into a head tank and in order that the high velocity from the pumps can be reduced and turbulence smoothed out, the flow passes through an egg crate grill. Water is delivered from this tank again through an egg crate to the test section, and then directly to the suction of the pumps. See Figure 1.

A number of difficulties in design were encountered and overcome by painstaking attention to details. It was found impossible to make a tight joint between the glass sides and the profiled brass blocks forming the Venturi section, and still have these plates absolutely flush with the walls of the approaching channel. Consequently, the design was altered by providing double windows whereby the inner plate preserved the flush surface, while water tightness was secured by gaskets between the outer window and the metal parts.

Great care had to be exercised in securing absolute tightness of all connections, and it was found that commercial fittings, cocks, etc., which were satisfactory for ordinary service had to be emersed in a water seal in order to exclude any possibility of air leaking in through joints. Particular attention was given to the methods of reading pressure, to be sure that no error could arise from the effect of water column in the piezometer connections. Traps and telltales had to be provided to secure proper drainage of all lines for both water and air. Fluctuations in pressure readings were dampened by the use of capillary tubes, in order that the friction through the connections should be the same in both directions, and should be effected primarily by the viscosity of the liquid rather than any throttling around sharp edges, such as cracked valves, which might lead to false readings.

The first experiments were made with the test section shown in Figure 2. Preliminary work was carried out with this form of passage, but it was found impossible to produce pitting to any marked extent on the glass, whereas the brass blocks came through absolutely unharmed, in spite of many hours of work during which apparently violent cavitation had been produced.

Advantage was taken of having the apparatus available to make careful pressure readings, which threw considerable light upon the characteristic curve of pressures at various stations along such a converging and expanding passage. This pressure curve is characterized, first, by a gradual and then a precipitous drop in pressure to the point of lowest pressure. Then, there is a similar regain, as long as cavitation is not formed, except of course that since the rate of diffusion is less than the rate of convergence, the gradient is by no means as steep. It was furthermore found that by taking as a reference, the pressure upstream from the test section at a point where the velocity of approach was practically negligible, the difference between this and the pressure at any piezometer tap was always proportional to the corresponding difference for any other tap. In other words, once knowing the pressure distribution for one velocity, the pressure at every other point could be accurately predicted, providing the pressure at one point under the new conditions were known. This rule held as long as the lowest pressure at any point in the system did not reach the vapor pressure of the water.

When the above condition was altered, either

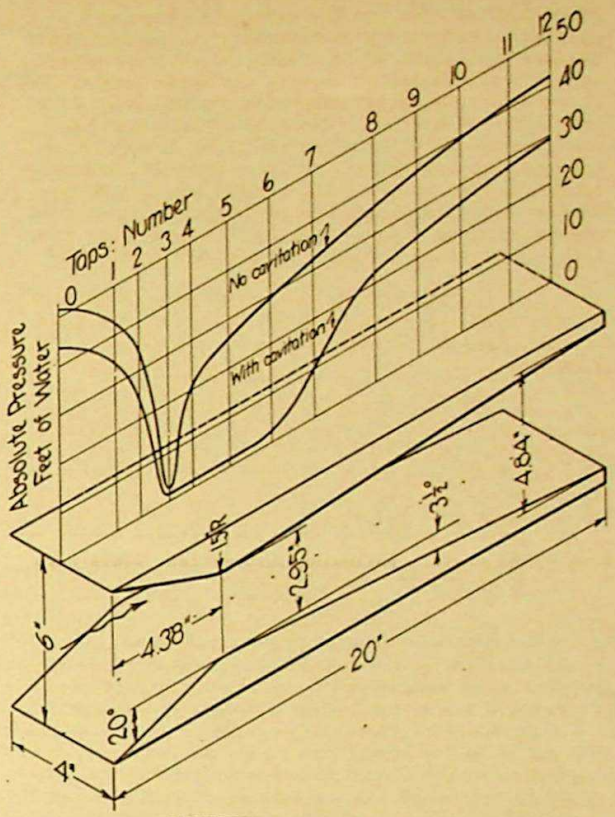

Fig. 2, Profile 1 and Typical Pressure Distribution Curves

by increasing the velocity with the same head pressure, or else by lowering the pressure in the system as a whole, the pressure distribution curve could be so depressed that the low point would reach the vapor pressure. Now, as it is impossible for pressures to exist below this in the presence of a turbulent liquid, the sharp point in the curve is necessarily flattened. Study of the progressive changes showed that the first alteration was simply a driving in or flattening of the point of low pressure. This was accompanied by a soft sizzling noise and the formation of two white fluffy clouds of bubbles at the throat.

Further increase of velocity, or decrease of pressure, produced then a curious effect upon the pressure distribution. After a limited amount of flattening of the point, the curve from entrance to the throat became absolutely stable and unaltered by subsequent change in pressure on the discharge side of the test section. The quantity of flow when computed was found to correspond to the free discharge into a complete vacuum. Below the throat the pressure was nearly uniform and about equal to the vapor pressure up to the point where there was a sudden recovery of pressure at the zone of collapse. From here the curve continued much as before. It was noticed that the rise in this pressure curve resembles very closely the water surface in a hydraulic jump, and it is believed that there is a similarity between the impulse of the high velocity water at low pressure striking a slowly moving body of water at higher pressure, and the jump.

A study was then made of pressure distribution and characteristics of profile shown in Figure 3. The principal change from profile 1 was the increase in flare and its termination in a parallel section 9⅛" from the throat, having a width of 4 5/8". One of the outstanding observations with this profile was that the noise resulting from the collapse of the bubbles was far more violent than before and that care had to be exercised to prevent failure of the glass plates. Consequently, only a limited number of conditions could be observed visually as the plates

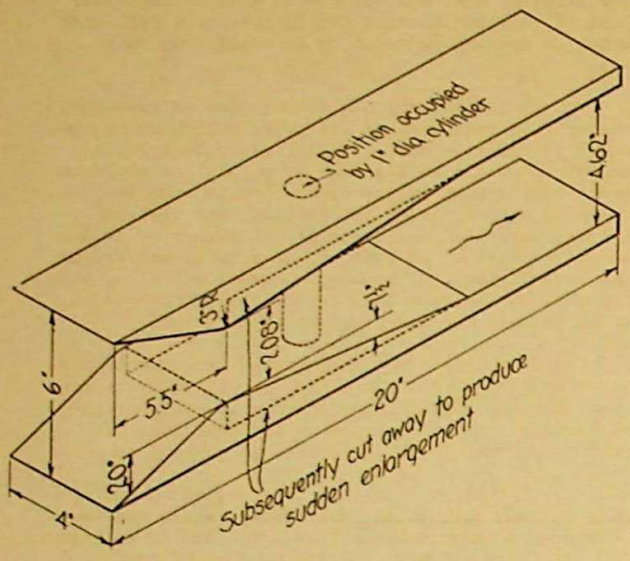

Fig. 3, Profile 2

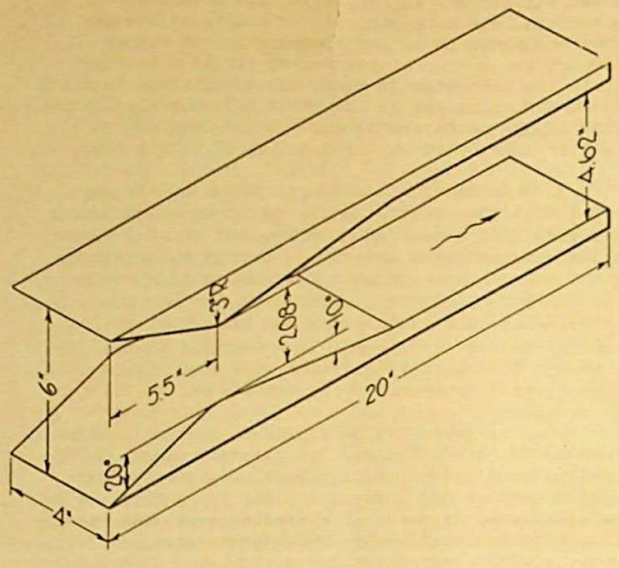

Fig. 4, Profile 3

quickly clouded and eventually were shattered. Even special case hardened glass clouded in about three-quarters of an hour exposure, so that it was felt unsafe to continue without risk of loss. On examination of this plate after removal, it was found that although ordinary glass had broken out at the surface, the case hardened glass had become deteriorated under the surface when once it had become penetrated. The damage had run sufficiently under the surface so that a number of pieces flaked off in very thin wafers. It would be interesting to know just how the destruction of the glass had taken place, whether by mechanical strain carried through the more resistant surface, or whether the destructive energy had been transmitted under the surface by means of highly compressed particles of air.

Although it was impossible to get glass to stand the punishment produced by the second profile, metal plates were substituted and the pressure distribution studies could go on, first having photographs taken to show the relation between the visual observation and the pressure distribution for lower velocities at which the glass windows could be used. While taking these photographs it was observed that there was a marked increase in noise when the pressure was adjusted to bring the collapse of the bubbles beyond the end of the flaring section.

This study of pressure distribution revealed an unexpected result. The fact previously noted, that without cavitation the differences between the reference pressure and the pressures at the piezometer openings remained always proportional to each other, was to be expected, although there was recognized the possibility that the influence of Reynolds' number with change of velocity might have had some disturbing effect. However, it was not expected that the laws of similitude would be obeyed in that terrifically turbulent mixture following the collapse of the bubbles. Strange to say, after the pressure had once begun to rise, this same proportionality still held, a fact which greatly facilitated the study of pressure distribution inasmuch as observations at any velocity could be reduced to standard conditions.

It was realized early in the work that account must be taken of the air contained in the water which, undoubtedly, has considerable influence upon the pressure in the bubbles and possibly the nature of the pitting. Little was known in regard to the behavior of water containing air when submitted to low pressure. Consequently, an analysis, mechanical instead of chemical, was made, by which means a small sample of water taken directly from the forebay tank could be submitted to the same physical treatment that it receives in passing through the zone of cavitation. The apparatus consisted of a small vessel connected to a calibrated burette in which a vacuum could be drawn by lowering a reservoir of mercury connected to it with the flexible tube. Although there were encoutered many difficulties, now overcome, arising from the fact that, as originally planned, the burette did not have sufficient capacity in proportion to that of small vessel, nevertheless some interesting experiments showed that air is released from water very readily with reduction of pressure.

Doctor Peters had found, for example, that if the upper part of the burette were filled with water under ordinary pressure and the reservoir then lowered, thus reducing the pressure, the water started to effervesce when the unbalanced column of mercury stood at approximately one-half the barometric height, or long before there would be any general boiling of the water as observed when the reservoir was lowered to extreme position. On restoring the pressure there was present a small bubble of air remaining at the top of the burette. This bubble, strange to say, showed no apparent tendency to redissolve, even though the temperature and pressure had been restored to that at which the air was originally contained. After trapping out this bubble, the remaining water was again subjected to the same treatment and again a small bubble remained, showing that the air had not been entirely extracted the first time. Continued repetitions of this treatment always resulted in a slight amount of air extracted. It would appear from this that possibly in the restoration of the pressure some of the air must have gone back into solution.

On the other hand it was observed that when the apparatus was allowed to stand over-night after the extracted air had been allowed to collect in the top of the small vessel, there was no measurable return of the air into solution. It thus appears that although air comes out of solution very readily and in spite of the fact that possibly some very small amount may return by absorption at the surface, nevertheless to redissolve air requires intimate contact or turbulence and probably an elapse of time necessary to complete the process. It seems logical, therefore, that as water approaches the zone of low pressure, first bubbles of air must form about which the vaporization of water commences. The bubbles, would therefore, contain a mixture of water vapor and air, and exert a pressure corresponding to the sum of the partial pressures of the air and water. In suddenly reaching a zone of higher pressure, at which steam condenses, it is very doubtful whether the air can return into solution with sufficient quickness to prevent it becoming the center upon which the energy of collapse is concentrated. It is, furthermore, un-

known whether the damage, which has been observed on materials, can be accounted for simply by the mechanical blow, or by the transmission of energy through the medium of compressed air as a carrier. It is the intention to carry out experiments in which the quantity of air in the water may be varied through wide limits to determine whether the destructive effect is influenced by the quantity of air in solution.

As mentioned above, it was at first supposed that the pressure would remain constant during the so-called zone of cavitation, but careful observations had indicated a very slight rise in pressure, which becomes more marked as the angle of flare in the expanding section is increased. It was observed also that the pressure at the throat was not exactly the vapor pressure, but a slight amount in excess. It was very important that this should be investigated, because in determining the coefficient of cavitation, sigma, as proposed by Dr. Thoma, only the vapor pressure is taken into account without regard to the air pressure. No information was available to show whether this slight increase in pressure caused by the presence of air was sufficient to be considered or not. If appreciable, it can readily be seen that experimental results obtained, for example at Holtwood, where for much of the time the water has been used in the condensers of the steam plant and therefore, not only warm but presumably fairly free of air, could not be applied without correction to conditions in the field where the river water may be at nearly freezing temperature and charged with air dissolved in its descent through rapids. The present indications are, however, that the effect is small, but nevertheless special care is now being taken to correlate any observed difference with the air content in the water. If, however, it were not for these experiments, we would be faced with just one more uncertainty in regard to the application of laboratory results to the field.

The apparatus which has been designed by Prof. Spannhake offers not only opportunity for fundamental research, studies of pressure distribution, etc., but also makes possible practical tests on materials by subjecting them to the effects of cavitation.

For experiments of this nature, it is of course desirable to use some means of accelerating the results and, therefore, Prof. Spannhake sought to produce the cavitation in as severe a form as possible. On completion of pressure distribution studies on profile 2, profile 3 was constructed exactly like its predecessor, except for a flare of 10°, terminating in a similar parallel section. See Figure 4. The noise of the cavitation was very appreciably greater and we were encouraged to feel that by increasing the flare still further, we should secure greater violence of collapse.

Wishing to attain the ultimate as early as possible, in order to standardize on conditions suitable for endurance tests on materials, the section was then changed to that of sudden enlargement by cutting away profile 2 at right angles as shown in Figure 3. Although we have been led to understand from European investigators that the phenomenon would be very unstable, nevertheless we were surprised that the violence of the cavitation was not great. We did get much of the same effect as had been observed before, near the throat as the water itself apparently supplied the portion where the metal had been cut away, but, the presence of a fluid instead of solid metal apparently gave sufficient flexibility to soften the entire process. In spite of the decreased activity, the plate glass windows were slowly clouded in a pattern similar to that which had been observed previously with profiles 2 and 3, but at a rate of approximately a tenth as fast. The axes of the pitted areas lay along the boundaries of the central stream and the eddies which filled in the square corners, which indicated that cavitation could take place between two layers of the liquid itself. It is possible that this is what happens when a jet of high velocity water fails to mingle readily with slow moving water around it, and may account for failure of a full size ejector to operate as would be expected from model tests.

In the experiments with sudden enlargement, no effect had been seen on the metal walls, and it was decided to insert a cast iron cylinder about 1" in diameter directly across the jet so that it would be actually surrounded by the zone of collapsing bubbles. Strange to say, although the cylinder was apparently receiving terrific punishment by being exposed to the most active part of cavitation, no pitting was found after several hours of exposure. Later bakelite, which is said to be superior to glass in indicating the pitting action, was found not to be affected.

It appears from the limited experience that has been gained so far, that the rise in pressure upstream from the stagnation point on the cylinder is sufficient to cause the collapse to occur just far enough away from the metal surface to protect it.

On failing to find a quick solution for producing extreme cavitation, the corners which had been cut away were progressively filled in, but it was not until the flare had been reduced to that of profile 3 that maximum violence was obtained, although possibly an optimum angle could have been found to lie somewhere between 10 and 20 degrees, as there was little difference between behavior with the last filler and profile 3 itself. It was concluded, therefore, that this latter would be satisfactory for the endurance tests on materials.

At present the possibilities of this work have hardly been touched upon. The only materials experimented with are glass, brass, cast iron, and semi-steel which were laid out on the laboratory table for inspection. It is apparent that glass is extremely vulnerable and the case hardened glass behaves very differently from ordinary plate glass as it apparently rotted away under the surface. The brass profile blocks had shown, in spite of hours of hard service, very little effect, although when examined under a stereoscopic microscope there could be seen dents which appeared as though the brass had suffered from severe and highly concentrated local pressures. These markings nevertheless are surprisingly few when we consider the number of severe collapses that must take place during the course of the experiments. There may be seen some trace of crushing of the metal around the piezometer taps, which caused semi-circular cracks and a slight movement inward of areas resembling crescent moons and having their axes parallel to the direction of flow.

In some of the tests, sheet brass about 1/8" thick backed by cast iron was used to serve as a standard for comparison. As these showed a tendency to bulge inward, the later ones were more securely fastened by numerous screws, but when these were taken out, the plate was found to be severely buckled, indicating that cavitation had put sufficient compression strain in the surface to result in a permanent set.

Cast iron and semi-steel were found to be affected by apparent eating away of the graphite leaving the perlite in minute lumps exposed in a way that resembled the surfaces of concrete in which there was not sufficient paste to fill in the spaces between the gravel.

There are a great many possibilities for the use of this apparatus, and effort is to be made to test the effectiveness of welding procedure as actually carried out in repair work. It is particularly desirable to study the bond between the parent metal and the weld, as well as to determine the necessity for grinding the weld smooth in finishing.

For further investigation a set of plates is being made for paint tests using the paints that are actually being applied to the runners at Safe Harbor. It was felt that slight differences in exposure at the different portions of the actual run-

ners might lead to false conclusions, and so it would be desirable to supplement these trials by tests made under strictly comparable conditions. On one of these plates grooves have been cut and then filled in with arc welded 18 - 8 steel by the men who do this work in the repair of runners at Holtwood[2].

In connection with some paint tests, interesting observations were made by virtue of the fact that the effects were apparent after a short time of exposure. Using a plate that had already been damaged beyond the junction of the flare and the parallel section, the back pressure was increased in order to bring the collapse nearer the throat where the paint was still undamaged. This incidentally gave a greater and more rapid rise in pressure, so that from the consideration of pressure alone, it would seem that conditions were even more severe than before. Strange to say, after an equal exposure no effect was seen. In order to confirm these results, the tests were repeated several times and it was found in a very striking way that although the area pitted beyond the flare could be appreciably enlarged by as little as half an hour of exposure, nevertheless no pitting could be made to take place in the expanding section.

It should be recalled that in the work with profile 1 which had no parallel section, no pitting had been produced at all, and that when profile 2 was first tried there was a marked increase in noise when the collapse was drawn out beyond this junction. The indications are that in order to have pitting, certain conditions must be fulfilled. As mentioned above, the cylinder exposed to the full fury of the oncoming flow and extending through the boundary where cavitation was evident from the pitting on the glass plate, and into the eddies formed in the square corners, came through undamaged even with the collapse of the bubbles taking place all around it. It would appear, from this, that there must be some protecting influence which is effective in preventing the damage. The nature of this influence is still not clearly understood, but it seems to be connected with a possible back wash or flow in the boundary layer which holds the collapse sufficiently distant from the surface to make it harmless. On the other hand it is possible that on the parallel surfaces near the junction this back wash is intermittently swept back so that the surface is exposed to the stream of collapsing bubbles.

As mentioned before, whatever pitting has occurred on the blades at Safe Harbor, with the exception of that on the leading edges, appears to be associated with slight depressions which are unavoidable in a rough casting. It is possible that a geometrically perfect blade might be able to withstand cavitation in considerable degree as long as the continuity of the boundary layer is preserved, but when this is broken by slight imperfections in contour it may give rise to pitting. This is of course simply an indication of some connection between the pitting observed on the blades and that found in the test stand, but this equipment makes possible further investigation into this obscure subject.

Another practical problem which is contemplated is a study of the influence of air not dissolved in the water but admitted into the test section through a piezometer tap. It has been known for a long time that air admission would increase the part gate output of Francis wheels. Later, as a result of index method tests reported by several members of the National Hydraulic Power Committee, it has been established fairly definitely that this increase is secured by improved efficiency rather than by increased discharge, and so is a real gain in economy. On the other hand, based upon the belief that pitting was caused by the release of oxygen which attacked the metal chemically, it is natural that operating men should have doubts concerning the advisability in introducing air which contains a large percentage of the gas that makes the trouble. It is intended to see whether pitting can be increased in this way or whether the resiliency of the air will cushion the collapse sufficiently to lessen the damage.

I do not wish to close without mentioning the paper "Design of Turbines and Pumps" which Prof. Spannhake presented at the Annual Meeting of the American Society of Mechanical Engineers, December 1932. Our engineers have given this considerable study and have extended the ideas which he suggested to apply to a plan for coordinating laboratory tests with the theoretical design considerations thus bridging, as far as possible, the gaps between theory and practice which Prof. Spannhake brings out so clearly.

It may be deduced from the studies he has made in the preparation of this paper that with propeller turbines, efficiency and capacity are so opposed that it seems impossible to design a single wheel that will secure the ultimate in both respects. The two objectives seem so far apart that it would be impossible to attain either one by any compromise.

To speak more specifically, he has shown that for high efficiency the blades of a turbine should be narrow in order to reduce skin friction and the drag of the blade moving through the water with high relative velocity, but on the other hand, from the standpoint of cavitation, the blades should be broad. Although some progress may be made, as Prof. Spannhake has proposed, in designing the curvature of the blade to secure equalization of the danger of cavitation, that is so that no one bad spot will limit the output of the machine on account of local low pressure, still we are faced with the fact that the width of the blade influences efficiency and cavitation in opposite directions.

On the other hand he has pointed out an important element in design, the value of forward whirl as advocated by Prof. Moody. This has been shown both by calculation and by laboratory and field tests to have a favorable influence on both efficiency and cavitation.

Model tests show, furthermore, that a high value of $\emptyset$ is conducive to high unit capacities, which are desirable in lessening the cost per horsepower, but on the other hand to take full advantage of the possibilities in this respect would necessitate operation at too high speed for peak efficiency.

So far very few plants have been installed with a deliberate choice of wheels of different characteristics. An outstanding example is the Norwood plant of the Carolina Power & Light Company, where Francis wheels of different specific speeds were used in order to get the broader efficiency characteristics of the lower speed wheel for the varying loads, while the higher speed wheels operate at nearly fixed loads, the whole loading schedule being controlled by the Kerr automatic operator. There is a plant on the Swiss French border where different characteristics were accidentally secured even though the same specifications were given to the two manufacturers. After the tests were made it was found that for a run-of-river plant this arrangement was ideal, as the highly efficient wheels could be used for low flow, whereas the units which had exceeded their guarantees in capacity could be used in times of flood. The question that I should like to leave with this committee is whether the propeller turbine has not brought us to face such an arrangement as one of the major design problems in future run-of-river power plants. Consideration should be given to the sacrifice of capacity in favor of efficiency for wheels that will be operated the greater part of the time, whereas for the others it would be possible to take still further advantage of higher specific speed and unit capacity by not being forced to compromise for the sake of efficiency which becomes of lesser importance at times when these units would be operated.

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[2] The morning after presentation of this paper there arrived at the laboratory two plates coated with soft rubber furnished by courtesy of the B. F. Goodrich Rubber Company, Akron, Ohio. It is believed that these are the first tests that have been made to determine the effect of cavitation on rubber under controlled conditions.